REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*
22-05-2001

2. REPORT TYPE
CONFERENCE PROCEEDINGS

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE
A FRAMEWORK FOR DATABASING 3D SYNTHETIC ENVIRONMENT DATA

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Roy Ladner, Mahdi Abdelguerfi, Ruth Wilson, John Breckenridge, Frank McCreedy and Kevin Shaw

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Naval Research Laboratory
Marine Geoscience Division
Stennis Space Center, MS 39529-5004

8. PERFORMING ORGANIZATION REPORT NUMBER
NRL/PP/7440--01-1004

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
NATIONAL IMAGERY AND MAPPING AGENCY AND THE U.S. MARINE CORPS WARFIGHTING LAB

10. SPONSOR/MONITOR'S ACRONYM(S)
NIMA AND MCWL

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT
Since 1994 the Digital Mapping, Charting and Geodesy Analysis Program at the Naval Research Laboratory has been developing an object-oriented spatial and temporal database, the Geographic Information Database (GIDBTM). Recently, we have expanded our research in the spatial database area to include three-dimensional synthetic environment (3D SE) data. This work has focused on investigating an extension to the National Imagery and Mapping Agency's (NIMA's) current Vector Product Format (VPF) known as VPF+. This paper overviews the GIDB and describes the data structures of VPF+ and a prototyped 3D synthetic environment using VPF +. The latter was designed as a 3D Geographic Information System (3D-GIS) that would assist the U.S. Marine Corps with mission preparation and also provide onsite awareness in urban areas.

2001092O 083

15. SUBJECT TERMS
3d-gis, vpf, vpf+, 3d synthetic environment

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
Unclassified	Unlassified	Unclassified		11	Roy Ladner

19b. TELEPHONE NUMBER *(Include area code)*
228-688-4679

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Title of Paper or Presentation
A FRAMEWORK FOR DATABASING 3D SYNTHETIC ENVIRONMENT DATA

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It is intended to offer this paper to the 12TH INTL CONFERENCE ON DATABASE AND EXPERT SYSTEMS APPLICATIONS
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Author(s) Ladner	Roy Ladner	5/18/01	
Section Head Shaw	KB Shaw	5/22/01	
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Division Head ~~Eppert~~ Acting 7400 Valent	Philip J. Valent	5/24/01	1. Release of this paper is approved. 2. To the best knowledge of this Division, the subject matter of this paper (~~has~~____) (has never X) been classified.
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A Framework for Databasing 3D Synthetic Environment Data

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Abstract. Since 1994 the Digital Mapping, Charting and Geodesy Analysis Program at the Naval Research Laboratory has been developing an object-oriented spatial and temporal database, the Geographic Information Database (GIDB™). Recently, we have expanded our research in the spatial database area to include three-dimensional synthetic environment (3D SE) data. This work has focused on investigating an extension to the National Imagery and Mapping Agency's (NIMA's) current Vector Product Format (VPF) known as VPF+. This paper overviews the GIDB and describes the data structures of VPF+ and a prototyped 3D synthetic environment using VPF+. The latter was designed as a 3D Geographic Information System (3D-GIS) that would assist the U.S. Marine Corps with mission preparation and also provide onsite awareness in urban areas.

1 Introduction

The Digital Mapping, Charting and Geodesy Analysis Program (DMAP) at the Naval Research Laboratory has been actively involved in the development of a digital mapping database through its Geospatial Information Database (GIDB™). The GIDB is an object-oriented, CORBA compliant spatial database capable of storing multiple data types from multiple sources [GIDB]. The data is accessible both locally and remotely over the web through a Java Applet.

Recently we have expanded our work in the spatial database area to include three-dimensional synthetic environment (3D SE) data. Our synthetic environment work has focused on investigating an extension to the National Imagery and Mapping Agency's (NIMA's) current Vector Product Format (VPF) known as VPF+. VPF+ adds a new level of topology called Level 4 Full 3D Topology (Level 4). The topologic information encompasses the adjacencies involved in 3D manifold and non-manifold objects, and is described using a new, extended Winged-Edge data structure called *3D Non-Manifold Winged-Edge Topology*. This new level of topology is in-

tended to facilitate the use of VPF in the 3D SE generation process by supporting a wide range of three-dimensional features expected to be encountered in a three-dimensional synthetic environment.

We have prototyped VPF+ in a 3D Geographic Information System (3D-GIS) that would assist the U.S. Marine Corps with mission preparation and also provide onsite awareness in urban areas. These operations require practice in physically entering and searching both entire towns and individual buildings. Our prototype, therefore, supplements the more traditional 2D digital-mapping output with a 3D interactive synthetic environment in which users may walk or fly across terrain, practice entry of buildings through doors and windows, and gain experience navigating the interiors of buildings.

2 DMAP's Spatial Database Experience

DMAP began investigating spatial database issues in 1994 with the development of the GIDB. The GIDB includes an object-oriented model, an object-oriented database management system (OODBMS) and various Spatial Analysis Tools. While the model provides the design of classes and hierarchies, the OODBMS provides an effective means of control and management of objects on disk such as locking, transaction control, etc. Spatial analysis tools include spatial query interaction, multimedia support and map symbology support. Users can query the database by area-of-interest, time-of-interest, distance and attribute. Interfaces are implemented to afford compatibility Arc/Info and Oracle 8i, among others.

Not only has the object-oriented approach been beneficial in dealing with complex spatial data, but it has also allowed us to easily integrate a variety of raster and vector data. Some of the raster data includes Compressed ARC Digitized Raster Graphics (CADRG), Controlled Image Base (CIB), jpeg and video. Vector data includes VPF, Shape, sensor data and Digital Terrain Elevation Data (DTED). The VPF data includes such NIMA products as Digital Nautical Chart (DNC), Vector Map (VMAP), Urban Vector Map (UVMAP), Digital Topographic Data Mission Specific Data Sets (DTOP MSDS), and Tactical Oceanographic Data (TOD).

Figure 1 gives an example of how the user may use this data over the web through the applet. The area-of-interest shown in the figure is for a portion of the U.S. Marine Corps Millennium Dragon Exercise that took place in September 2000 in the Gulf of Mexico. Using the applet interface to the GIDB the user was able to access the area of interest, bring in CIB imagery and overlay it with various vector data from DNC, MSDS and survey data from the Naval Oceanographic Office. The user was then able to zoom in and replace the CIB with CADRG imagery, and then zoom in further to see more of the detail of the MSDS data around the harbor in Gulfport, Mississippi.

In addition to spatial query features, the GIDB is capable of temporal query, such as wave height over a given time span for spatial objects (for instance, an ocean sensor), to provide statistics (min, max, mean, standard deviation) of this data and to provide data plots.

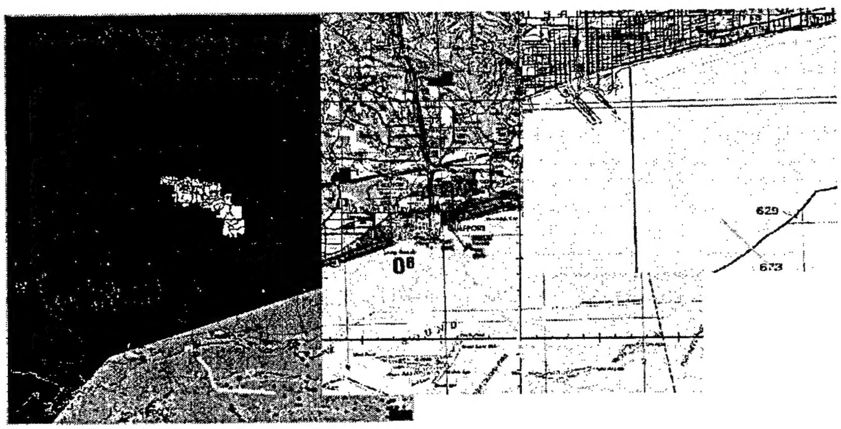

Fig. 1. Screen shots from Millennium Dragon exercise area. From left to right: **(1a)** CIB background with VMAP, DTOP MSDS, sensor data and DNC added. **(1b)** CADRG Data added, area-of-interest zoomed in. **(1c)** Additional zoom with CADRG and sensor data.

3 Motivations for the Current Work

NIMA is the primary provider of synthetic environment data to the Department of Defense and to the private sector. VPF and DTED are the formats used by NIMA to disseminate a significant amount of that data. Despite the widespread use of VPF, its shortcomings have been documented in the synthetic environment database generation systems used by a variety of government and private groups, involving different proprietary end-product formats, and across varying user needs [Trott 96]. These shortcomings involve VPF's arrangement of features into disjointed, thematic layers, its lack of attribute and geometric data appropriate to the reconstruction many 3D objects and its often lack of correlation with DTED data. Disjointed thematic feature data, in particular, requires considerable preprocessing and data integration to be usable in a 3D synthetic environment. These shortcomings add much time and money to the process of constructing synthetic environments from VPF data.

Non-manifold objects are those in which one of the following conditions exist: (1) exactly two faces are not incident at a single edge, (2) objects or faces are incident only through sharing a single vertex, or (3) a dangling edge exists [Gursoz 90, Lienhardt 91, and O'Rourke 95]. A dangling edge is one in which the edge is not adjacent

to any face. Examples are given in Figure 2 where non-manifold conditions are noted by the bold edges. Non-manifold objects are commonplace in the real world, and they should be found in a synthetic environment (SE).

VPF uses winged-edge topology to provide line network, face topology and seamless coverages across tile boundaries [VPF 96]. However, it lacks the constructs necessary to maintain the adjacency relations in non-manifold objects. While an edge is adjacent to exactly two faces in VPF Level 3 topology, an edge may be adjacent to 0, 1, 2, 3 or more faces in a SE when a non-manifold condition is present. Though the winged-edge topology used by VPF relates each edge to exactly two faces (left and right, corresponding to two adjacent faces), the concept of a "left" and "right" face may be lacking in 3D non-manifold objects where multiple faces may be incident to the edge.

VPF also relates each connected node to exactly one of the edges to which each such node is connected. This allows for retrieval of all edges and faces to which the node is connected using the winged-edge algorithm. However, in a SE a connected node may connect two different 3D objects, two different faces or a dangling edge. Relating the connected node to only one edge in these circumstances will not be adequate for retrieval of all spatial primitives.

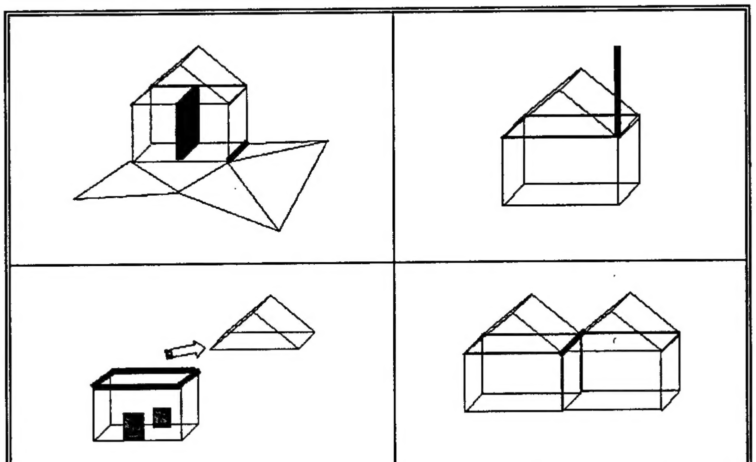

Fig. 2. Clockwise from top left: **(2a)** Multiple Faces Incident at a Single Edge. **(2b)** Dangling Edge and Building Joined Only By a Common Point. **(2c)** Two Buildings Sharing a Face With a Non-Manifold Condition at the bold Edge. **(2d)** Partial Building Creates Non-Manifold Condition.

There are a number of data structures that are capable of maintaining the adjacency relationships found in manifold and non-manifold objects. Notable are the Radial Edge [Weiler 86], the Tri-Cyclic Cusp [Gursoz 90] and the ACIS Geometric Modeler [Spatial 96]. The Radial Edge Structure is an edge based data structure that addresses

topological ambiguities found with two non-manifold situations - the non-manifold edge and the non-manifold vertex. The Tri-Cyclic Cusp Structure is a vertex based data structure. This data structure addresses the topological relationships that the Radial Edge Structure addresses, and, in addition, is specifically intended to resolve ambiguities inherent in certain non-manifold representations that may not be easily eliminated by the Radial Edge structure as when two objects are joined only at a common point. The ACIS Geometric Modeler is a component-based package consisting of a kernel and various application based software components.

While these may provide a theoretical basis for a logical extension of the VPF standard, they could not be directly implemented. Our primary area of concern is modeling synthetic environments. These other data structures address a different application area, solid modeling, making them often inconsistent with Winged-Edge topology concepts found in the VPF standard.

There are also a number of major developers of synthetic environment database systems such as Loral Advanced Distributed Simulation, Inc., Lockheed Martin Information Systems (LMIS), Multigen, Inc., Evans & Sutherland (E&S) and Lockheed Martin Tactical Defense Systems (LMTDS). Their products include database formats such as the S1000, OpenFlight, TARGET, and specific image generator formats. Their emphasis, however, is on visual representation, not three-dimensional topological relationships.

4 The VPF+ Data Structure

Since VPF has widespread use and there are numerous VPF databases, the data structures described in this section are defined as a superset of VPF, known as VPF+, in order to facilitate the use of VPF in the 3D SE generation process. This superset introduces a new level of topology called Level 4 Full 3D Topology (Level 4) to accomplish 3D modeling. A boundary representation (*B-rep*) method is employed. B-rep models 3D objects by describing them in terms of their bounding entities and by topologically orienting them in a manner that enables the distinction between the object's interior and exterior.

The topologic adjacencies of three-dimensional manifold and non-manifold objects in the SE are described using a new, extended Winged-Edge data structure, referred to as *"Non-Manifold 3D Winged-Edge Topology"*. Geometric information includes both three-dimensional coordinates and Face and Edge orientation. Although this discussion is restricted to planar geometry, curved surfaces can also be modeled through the inclusion of parametric equations for Faces and Edges as associated attribute information.

Level 4 is a full 3D topology that is capable of representing comprehensive, integrated 3D synthetic environments. Such an environment can include the terrain surface, objects generally associated with the terrain surface such as buildings and roads, and it can include objects that are not attached to the terrain but are rather suspended above the terrain surface or below a water body's surface.

4.1 VPF+ Topologic Structures

There are five main VPF+ primitives found in Level 4 topology: (1) *Entity node* – used to represent isolated features; (2) *Connected node* – used as endpoints to define edges; (3) *Edge* – an arc used to represent linear features or borders of faces; (4) *Face* – a two-dimensional primitive used to represent a facet of a three-dimensional object such as the wall of a building; and (5) *Eface* – a primitive that describes a use of a face by an edge. Unlike the topology of traditional VPF, the Level 4 topology of VPF+ does not require a fixed number of faces to be incident to an edge. The *Eface* is a new primitive that is introduced to resolve some of the ensuing ambiguities. Efaces describe a use of a Face by an Edge and allow maintenance of the adjacency relationships between an Edge and zero, one, two or more Faces incident to an Edge. This is achieved in VPF+ by linking each edge to all faces connected along the edge through a circular linked list of efaces. Each eface identifies the face it is associated with, the next eface in the list and the "next" edge about the face in relation to the edge common to the three faces. Efaces are also radially ordered in the linked list in a clockwise direction about the edge in order to make traversal from one face to the radially closest adjacent face a simple list operation.

In addition to the eface structure, VPF+ introduces several extensions to VPF consistent with non-manifold topology and 3D modeling. One extension is the Node-Edge relationship. While VPF relates each Connected Node to exactly one Edge, VPF+ allows for non-manifold Nodes. This requires that a Node point to one Edge in each object connected solely through the Node and to each dangling Edge (an edge that is adjacent to no face). This relationship allows for the retrieval of all Edges and all Faces in each object and the retrieval of all dangling Edges connected to the Node.

Significant to 3D modeling, VPF+ defines Two-Sided Faces. Faces are defined in VPF as purely planar regions. In VPF+ Faces may be one sided or two sided. A two sided Face, for example, might be used to represent the wall of a building with one side used for the outside of the building and the other side for the inside of the building. Feature attribute information would be used to render the two different surface textures and color. A one sided Face might then be used to represent the terrain surface.

Additionally, orientation of the interior and exterior of 3D objects is organized in relation to the normal vector of Faces forming the surface boundary of closed objects. This allows for easy distinction between an object's interior and exterior.

For more detail on VPF+ topologic structures the interested reader is referred to [Abdelguerfi 98].

4.2 Features in VPF+

Traditional VPF defines five categories of cartographic features: Point, Line, Area, Complex and Text. Point, Line and Area features are classified as Simple Features, composed of only one type of primitive. Each Simple Feature is of differing dimensionality: zero, one and two for Point, Line and Area Features respectively. Unlike

Simple Features, Complex Features can be of mixed dimensionality, and are obtained by combining Features of similar or differing dimension.

For Level 4 topology, VPF+ adds a new Simple Feature class of dimension three. The newly introduced feature, referred to as *3D Object Feature*, is composed solely of Face primitives. This new feature class is aimed at capturing a wide range of 3D objects. Although 3D Objects are restricted to primitives of one dimension, 3D Objects of mixed dimensionality can be modeled through Complex Features using Simple Features of similar or mixed dimensionality as building blocks.

Software performance can be improved by identifying characteristics of real 3D objects that will allow storage of optional, unambiguous topological information that may otherwise require considerable processing time to derive. Clearly, portions of numerous 3D objects form closed volumes that divide 3D space into interior, exterior and surface regions. Optional topological information in these cases includes the classification of Faces as either inside of, outside of or part of the boundary of the 3D Object and the orientation of the interior and exterior of the object.

Though Area Features may geometrically exist in 3D space, they are topologically two dimensional, and are intended to model surface area. As with 3D Object Features, Area Features are Simple Features, and objects being modeled at this level are restricted to be composed only of Faces connected along incident Edges or at non-manifold Connected Nodes. Each face may be single sided or double sided, but an Area Feature will generally make use of only a single side of a double sided Face.

4.3 Cross-Tile Topology

Tiling is the method used in VPF to break up large geographic data into spatial units small enough to fit the limitations of a particular hardware platform and media. Primitives that cross tile boundaries are split in VPF, and topology is maintained through *cross-tile topology*. The cross-tile constructs of VPF are extended in Level 4 in accordance with the organizational scheme of Non-Manifold 3D Winged-Edge topology. Tile boundaries in VPF+, however, consist of planar divisions.

5 The Prototyped Synthetic Environment

The synthetic environment prototype consists of the Military Operations in Urban Terrain site at Camp LeJeune, North Carolina. The MOUT site is a small city built by the Marine Corps for urban combat training. The MOUT site consists of approximately 30 buildings constructed in a variety of shapes and sizes to resemble what might be expected in an actual urban area. Since the area is supposed to resemble a combat environment, some are constructed to exhibit various degrees of damage. There is also a transportation network and the usual urban features associated with this type of setting such as trees, park benches, planters, flag poles, etc. Data for the site is readily available, which allowed for construction of a detailed 3D SE that closely

matched its real world counterpart. MOUT buildings that exhibit damage, for example, are reproduced in the prototyped SE to show the same elements of damage.

The prototype provides a 3D synthetic environment alongside a more traditional 2D digital map. The map view offers general orientation and feature identification, while the 3D SE complements this with an immersive experience of the three-dimensional environment [Ladner 2000]. The combination should prove beneficial to a variety of uses.

A commercial-off-the-shelf OODBMS was used for the prototype database. Java2 and the Java3D API were used for interface into the database. The Java3D API provided reasonable performance for 3D interaction and easy implementation.

5.1 The User Interface

The user interface for the prototype consists of windows for displaying 2D digital maps and 3D synthetic environments. Each window is placed in a separate frame to allow for independent re-sizing according to the user's needs. On start-up, the user is given a map of the world, which allows selection of a user-defined area of interest (AOI) by dragging the mouse across and down the map.

Selection of an AOI causes the database to be queried. A digital map is drawn with all database features (Figure 3(a)). The user then has several options including zoom, pan, render features in 3D and identify objects. Rendering objects in 3D was left to a user decision rather than a default occurrence for performance reasons. Although the user can render all features in 3D, the user is given the choice of zooming and panning the map as a means of selecting features for 3D display. Only those features within the AOI are rendered in 3D, avoiding the unnecessary use of resources to extract unwanted feature geometry from the database.

Figures 3(b) - 5 show the 3D SE of the MOUT facility from various positions. The interface allows the user to move through the SE and into and out of buildings by use of the arrow keys. Movement can be by walking on or flying above the terrain. Drop-down menus allow the user to change speed, background texture and lighting conditions. Altering lighting conditions allows the viewer, for example, to obtain both day and night views of the 3D SE.

A feature is also provided that allows the user to track his position in the 3D SE. When activated, this feature places an icon on the map corresponding to the user's position in the 3D SE. As the user moves through the SE, the position of the icon is updated. The icon is oriented to correspond to the user's orientation in the SE.

6 Observations

This paper has described VPF+, a VPF-consistent data structure capable of supporting topologically consistent three-dimensional feature coverage. VPF Winged-Edge topology is insufficient to support the many topological adjacency relationships found in the 3D SE. The Non-Manifold 3D Winged-Edge Topology will support these rela-

tionships in a wide range of objects likely to be modeled in a 3D SE and provides a framework for the 3D synthetic environment generation process. VPF+ should be useful for commercial as well as the more traditional modeling and simulation applications, especially for developers who want to extend their geographic information system capability to add 3D topology.

Detailed data in the form of highly accurate representations of the interior and exterior of buildings was used in the prototype. Some SE applications do not require building interiors. For these, building exteriors with accompanying topology suffices. VPF+ topology will support these implementations as well. Continuing research into improved methods of automating the extraction of detailed 3D object geometry from satellite, aerial and panoramic imagery should be beneficial for providing detailed data over large areas, at least for building exteriors. On smaller areas, digitizers can be used to re-construct building interiors from building plans or CAD data can be imported. Where building plans are not available or where more rapid development is required, further work can concentrate on developing tools to project the interior layout of buildings based on photo-imagery, the building use and a basic material composition description, i.e. steel, brick, frame. This type of description should be easily obtainable.

7 Acknowledgments

The National Imagery and Mapping Agency and the U.S. Marine Corps Warfighting Lab sponsored this work.

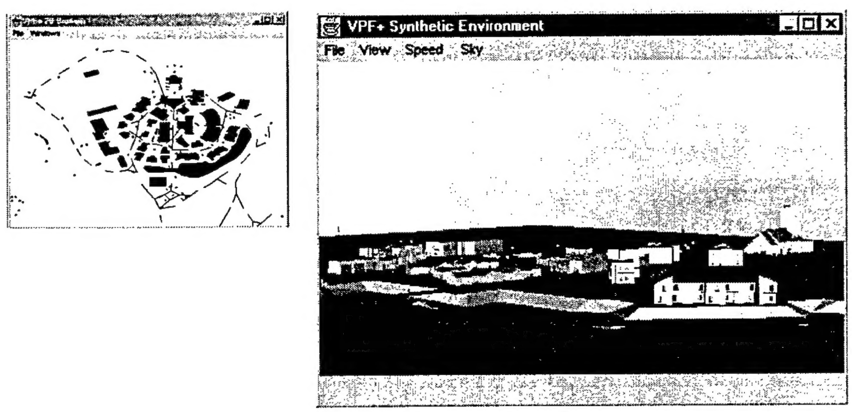

Fig. 3. From Left: **(3a)** 2D Map of the MOUT Facility. **(3b)** 3D View of the MOUT Facility from the Southwest.

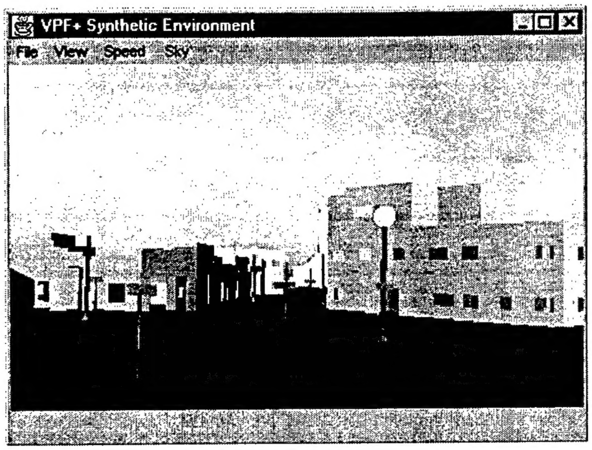

Fig. 4. Street View of the MOUT Facility Looking North.

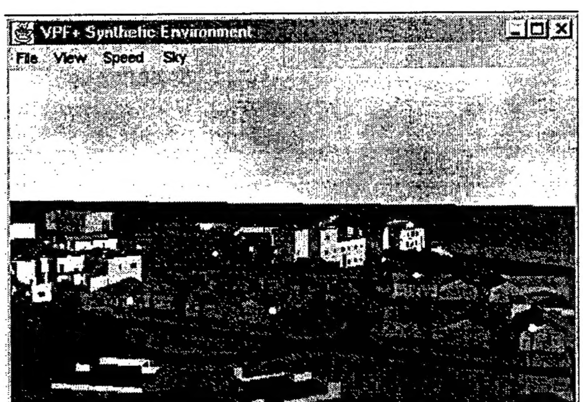

Fig. 5. View of the M OUT Facility from the West.

8 References

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